AD-A094 018 NORTHWESTERN UNIV EVANSTON IL DEPT OF ELECTRICAL ENG--ETC F/G 4/1
LOWTRAN V SUBROUTINE FOR THE CALCULATION OF INTENSITY DEVIATION--ETC(U)
SEP 80 C F OUYANG, M A PLONUS, S WANG F19628-79-C-0068

UNCLASSIFIED AFGL-TR-80-0297 NL

1 OF 1
AD A
094018

END
DATE
FILMED
2-81
DTIC

AD A094018

(12)

AFGL-TR-80-0297

LOWTRAN V SUBROUTINE FOR THE CALCULATION OF INTENSITY DEVIATION FOR POINT AND FINITE APERTURE RECEIVERS

LEVEL II

C. F. Ouyang
M. A. Plonus
S-J Wang

Northwestern University
Department of Electrical Engineering
and Computer Science
Evanston, Illinois 60201

Final Report
(period covered 2 Jan 1979 - 30 June 1980

September 1980

AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AFB, MASSACHUSETTS 01731

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	AFGL-TR-80-0297
2. GOVT ACCESSION NO.	AD-A094018
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle)	LOWTRAN V SUBROUTINE FOR THE CALCULATION OF INTENSITY DEVIATION FOR POINT AND FINITE APERTURE RECEIVERS.
5. TYPE OF REPORT & PERIOD COVERED	Final 2 Jan 1979 - 30 June 1980
6. PERFORMING ORG. REPORT NUMBER	
7. AUTHOR(s)	C. F. Ouyang M. A. Plonus S-J Wang
8. CONTRACT OR GRANT NUMBER(s)	F19628-79-C-0068
9. PERFORMING ORGANIZATION NAME AND ADDRESS	Northwestern University Dept. of Electrical Engr., and Computer Sciences Evanston, Illinois 60201
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS	62101F 767014AD
11. CONTROLLING OFFICE NAME AND ADDRESS	Air Force Geophysics Laboratory Hanscom AFB, Massachusett 01731 Monitor/Robert W. Fenn/OPA
12. REPORT DATE	September 1980
13. NUMBER OF PAGES	24
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	
15. SECURITY CLASS. (of this report)	unclassified
15a. DECLASSIFICATION DOWNGRADING SCHEDULE	

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Atmospheric turbulence
Transmittance variance
Atmospheric optics
Infrared
Visible

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes a coded subroutine for predicting atmospheric transmittance deviation due to the turbulence effect. This subroutine is designed to be used with Lowtran V. The calculation of transmittance deviation is for point receivers as well as for finite aperture receivers which exhibit the aperture averaging effect.

DD FORM 1 JAN 73 1473

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

SECURITY CLASSIFICATION OF THIS PAGE(*When Data Entered*)

SECURITY CLASSIFICATION OF THIS PAGE(*When Data Entered*)

CONTENTS

The subroutine for the calculation of intensity deviation in Lowtran V

I. Introduction

In this report, we present theoretical formulas and a coded subroutine for the calculation of intensity deviation which shows the high bound and low bound of the atmospheric transmittance due to the turbulence effect. In the subroutine, we calculate the transmittance deviation for point receivers as well as for finite aperture receivers which exhibit the aperture averaging effect.

Depending on the type of propagation paths, the calculation in the subroutine has been divided into three parts-horizontal, upward and downward paths, similarly to the transmittance calculation in Lowtran V program.[1] The different examples will be shown and compared in the following section.

II. Plane wave intensity deviation for point receivers

Consider a plane wave U propagating through the turbulent medium represented by

$$U = e^{\chi + iS} \tag{2.1}$$

where χ is a real value that represents the log-amplitude and S is the imaginary part that represents the phase. Assuming the Gaussian probability distribution for χ, the average intensity and variance of intensity can then be stated as

$$\langle I \rangle \equiv \langle U \cdot U^* \rangle = \langle e^{2\chi} \rangle = e^{2(\sigma_\chi^2 + \langle \chi \rangle)} \tag{2.2}$$

$$\langle I^2 \rangle \equiv \langle U \cdot U^* \cdot U \cdot U^* \rangle = e^{4\langle \chi \rangle + 8\sigma_\chi^2} \tag{2.3}$$

where $\langle\ \rangle$ denotes an ensemble average and $\sigma_\chi^2 \equiv \langle(\chi - \langle\chi\rangle)^2\rangle$. Using Eq. (2.2) and (2.3), the normalized variance of the intensity fluctuations is given by

$$\sigma_I^2 \equiv \frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2} = e^{4\sigma_\chi^2} - 1 \qquad (2.4)$$

The variance of log-amplitude, σ_χ, has been found by Rytov's Method.[2] However, it is only valid for weak turbulence when applied in Eq. (2.4). Experimental data[2] indicates that σ_I is saturated toward the value of unity. In recent years theoretical work to proof that the variance of intensity saturates to a constant of unity was performed.[3] Avoiding complex mathematics and hoping to get a model which is sufficiently accurate under weak and strong turbulence conditions, we relate the variance of intensity and log-amplitude by[4]

$$\sigma_I \approx 1 - e^{-2\sigma_\chi} \qquad (2.5)$$

For small values of σ_χ, $\sigma_I = 2\sigma_\chi$ which agrees with equation (2.4). For large σ_χ, $\sigma_I \approx 1$, which agrees with the saturation condition. After we determine σ_I, the upper bound and lower bound of transmittance can be calculated by

$$T_{u,\ell} = T(1 \pm \sigma_I) \qquad (2.6)$$

using Ref. (2), the variance of log-amplitude as found by Rytov's Method is given by

$$\sigma_\chi^2 = .563k^{7/6}\int_0^L d\eta\, C_n^2(\eta)(L-\eta)^{5/6} \qquad (2.7)$$

where k is the wavenumber, L is the path length and C_n^2 is the structure constant of refractive index. When C_n^2 is constant along the path, Eq. (2.7) can be rewritten as

$$\sigma_\chi^2 = .31\, C_n^2(h)k^{7/6}L^{11/6} \qquad (2.8)$$

The structure constant C_n^2 has been measured and modeled by Hufnagel, et. al.[5]

we have modified it to fit in Lowtran as

$$C_n^2 (h) = \begin{cases} 4.2 \times 10^{-14} h^{-2/3} \exp(-h/320) & (h > 10m) \\ 8.77 \times 10^{-15} & (h < 10m) \\ 0 & (h > 100km) \end{cases} \qquad (2.9)$$

where h is altitude and is in units of meters.

For horizontal path, h is constant, hence we use Eq. (2.8). For downward (and upward) path, we must use Eq. (2.7) in which the integral shows an integration from transmitter to receiver. From the weight function $(L-\eta)^{5/6}$ in Eq. (2.7) we know the turbulence around transmitter has more effect than the turbulence near the receiver. Hence we predict that a downward path has larger variance of intensity than an upward path for the same length of path.

For the program, we rewrite Eq. (2.7) in summation form as

$$\sigma_\chi^2 = .56k^{7/6} \sum_i \sum_j C_n^2 (h_{ij}) (L-L_{ij})^{5/6} \frac{\Delta L_i}{h_i - h_{i-1}} \Delta h_{ij} \qquad (2.10)$$

$$\begin{array}{rl} h_{ij} < 25km & \Delta h_{ij} = 20m \\ 25km < h_{ij} < 50km & \Delta h_{ij} = 100m \\ 50km < h_{ij} < 100km & \Delta h_{ij} = 400m \end{array}$$

where h_{ij} is the altitude corresponding to the calculated point of the path, "i" is the layer index, "j" is the sub index of each layer, L is the total path length, L_{ij} is the path distance from transmitter to the point calculated and ΔL_i is the path length for each layer passed. The choice of Δh intervals was made to allow better height resolution in future specifications of $C_n^2(h)$.

In this calculation, we assume that the path in each layer is straight. Refraction occurs only at the boundaries. The refraction calculation is executed by the original Lowtran program.

Figs. (2.1), (2.2) and (2.3) show the transmittance predicted by Lowtran V with the deviation calculated by the added subroutine for horizontal, downward and upward path, respectively. These calculations are for point receivers and a 5km path length. We find that the deviation for downward path is larger than that for upward. This is due to the stronger turbulence at the lower altitude and the effect that turbulence near the transmitter is dominant.

III. Intensity deviation for finite aperture receivers

In Sec. II, the intensity fluctuations are assumed to be measured by a point receiver. However, in the real world the receiver has a finite aperture. If the diameter of the objective is much larger than the amplitude correlation distance ρ, the objective will contain wave front sections with fluctuations of opposite sign, so that the overall light flux through a larger objective will fluctuate relatively weakly compared to the flux through a small (compared to ρ) objective.

Consider the intensity in the receiver plane to be $I(L, \underline{p})$. The total flux P through the objective is then $P = \iint_{\Sigma} I(L, \underline{p}) d\underline{p}$, where $\underline{p}$ is the transverse coordinate and Σ is the aperture area of the objective. The fluctuations in P, defined as $P = P - \langle P \rangle$, are expressed in the form $P' = \iint_{\Sigma} I'(L,\underline{p})\, d\underline{p}$, where $I' = I - \langle I \rangle$. For the mean square fluctuations of power we have

$$\langle P'^2 \rangle = \int_{\Sigma}\cdots\int_{\Sigma} \langle I'(\underline{p}_1)\, I'(\underline{p}_2)\rangle\, d\underline{p}_1\, d\underline{p}_2$$

$$= \int_{-\infty}^{\infty}\cdots\int B_I(\underline{p}_1 - \underline{p}_2)\, F(\underline{p}_1)\, F(\underline{p}_2)\, d\underline{p}_1\, d\underline{p}_2 \qquad (3.1)$$

where the intensity correlation function $B_I(\underline{p}_1 - \underline{p}_2) \equiv \langle I'(\underline{p}_1)\, I'(\underline{p}_2)\rangle$ and $F(\underline{P})$ is a function which is zero outside the aperture and 1 on its surface.

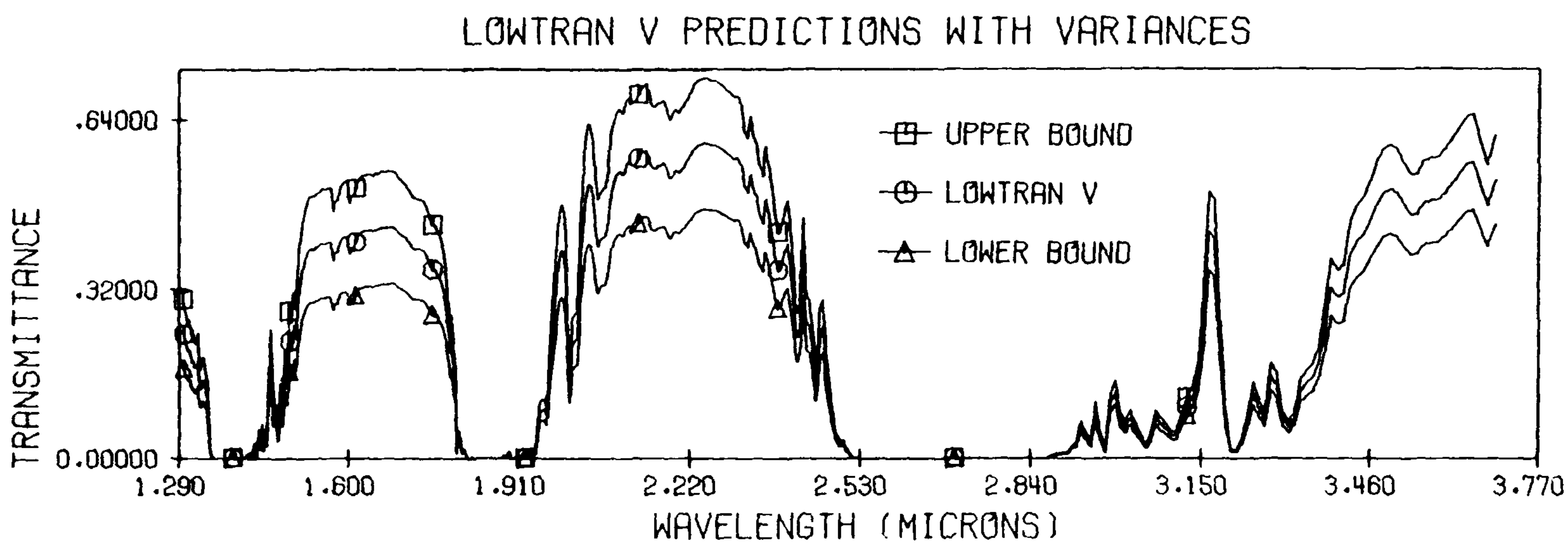


Fig. 2-1 Atmospheric transmittance predicted by LOWTRAN V with upper and lower bound using 1962 U.S. standard atmospheric model and Rural aerosol model for a 5 km horizontal path at altitude 400 m, and visual range 5 km for a point receiver ($D = 0$).

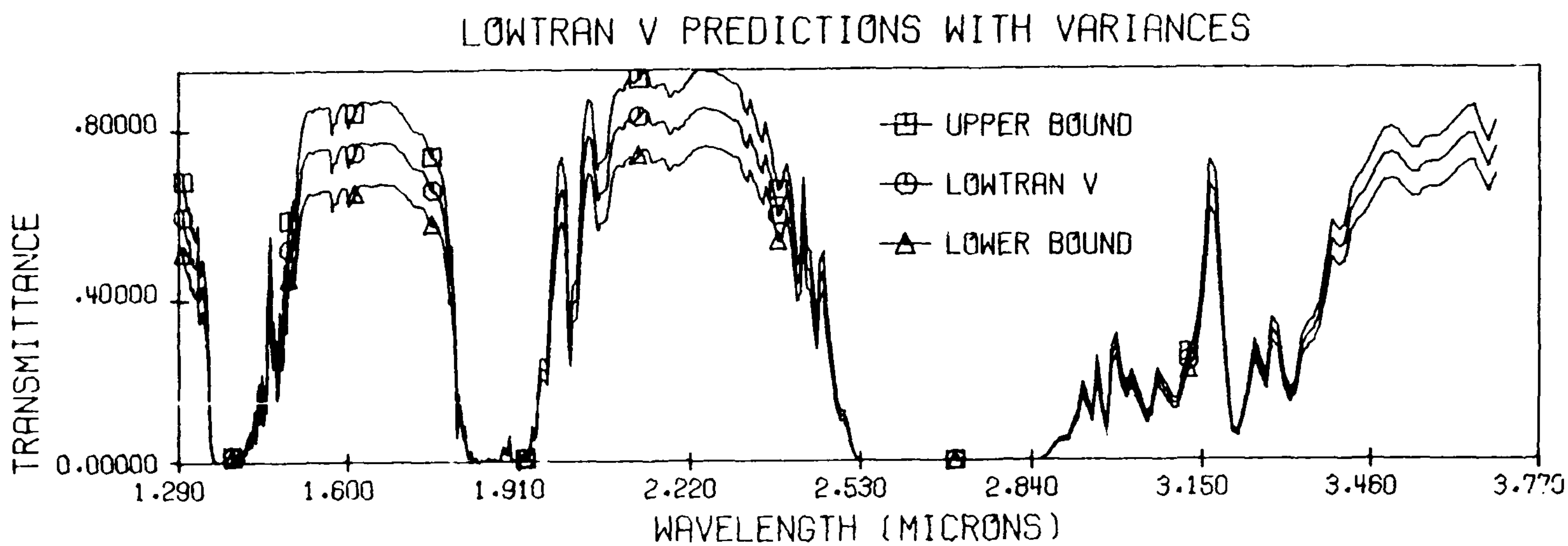


Fig. 2-2 Atmospheric transmittance predicted by LOWTRAN V with upper and lower bound using 1962 U.S. standard atmospheric model and Rural aerosol model for a downward path at altitude from 200 m to 4 km with path length of 5 km, and visual range 5 km for a point receiver.

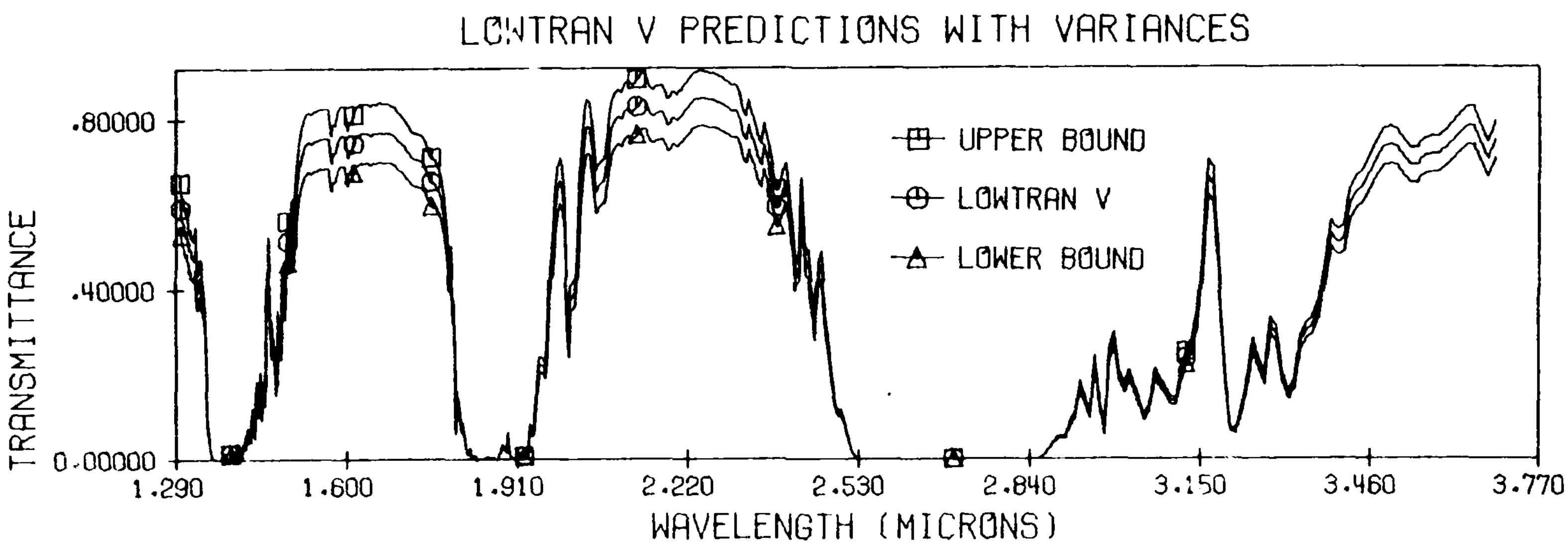


Fig. 2-3 Atmospheric transmittance predicted by LOWTRAN V with upper and lower bound using 1962 U.S. standard model and Rural aerosol model for an upward path at altitude from 4 km to 200 m with path length of 5 km, and visual range 5 km for a point receiver.

Changing variables and assuming the receiver aperture to be a circle with radius R, Eq. (3.1) can then be written as:

$$\langle P'^2 \rangle = 2\pi \int_0^{2R} \rho d\rho \; B_I(\rho) \; K(\rho) \tag{3.2}$$

where

$$K(\underline{\rho}) \equiv \int_{-\infty}^{\infty}\int F(\underline{p}_1) \; F(\underline{p}_1 - \underline{\rho}) \; d^2\underline{p}_1$$

$$= \begin{cases} 2R^2 \left[\cos^{-1}\left(\frac{\rho}{2R}\right) - \frac{\rho}{2R}\sqrt{1 - \frac{\rho^2}{4R^2}}\right], & \rho < 2R \\ 0, & \rho > 2R \end{cases} \tag{3.3}$$

The normalized fluctuation of power is defined as

$$Q(R) \equiv \frac{\langle P'^2 \rangle}{\langle P \rangle^2} = \frac{4}{\pi R^2}\int_0^{2R} \frac{B_I(\rho)}{\langle I \rangle^2}\left[\cos^{-1}\left(\frac{\rho}{2R}\right) - \frac{\rho}{2R}\sqrt{1 - \frac{\rho^2}{4R^2}}\right]\rho d\rho \tag{3.4}$$

to show the averaging action, we define another parameter $G(R) \equiv \frac{Q(R)}{Q(0)}$ which is a ratio that compares the fluctuations of power of a finite aperture and a point aperture:

$$G(R) = \frac{4}{\pi R^2}\int_0^{2R} b_I(\rho)\left[\cos^{-1}\left(\frac{\rho}{2R}\right) - \frac{\rho}{2R}\sqrt{1 - \frac{\rho^2}{4R^2}}\right]\rho d\rho \tag{3.5}$$

where $b_I(\rho)$ is the normalized correlation coefficient of the intensity fluctuations

$$b_I(\rho) \equiv \frac{\dfrac{B_I(\rho)}{\langle I \rangle^2}}{\dfrac{B_I(0)}{\langle I \rangle^2}} = \frac{e^{4B_\chi(\rho)} - 1}{e^{4\sigma_\chi^2} - 1} \tag{3.6}$$

and

$$B_\chi(\rho) \equiv \langle \chi(\underline{p}_1)\chi^*(\underline{p}_2) \rangle \tag{3.7}$$

Because the structure constant C_n^2 depends on the altitude h, the calculations for horizontal and downward or upward paths are different. We separate the two cases as follows:

(i) Horizontal path

By using Rytov's Method and the Kolmogorov spectrum (Refs. 2,6), $B_\chi(\rho)$ can be found with the condition that $\ell_o^2 << \lambda L$ as

$$B_\chi(\rho) = b_\chi(\rho)\sigma_\chi^2 \tag{3.8}$$

and

$$b_\chi(\rho) = \begin{cases} 1 - 12.3 \dfrac{\rho^2}{(\lambda L)^{5/6} \ell_0^{1/3}} & , \quad \rho << \ell_0 \\ 1 - 2.36(\dfrac{\rho^2 k}{L})^{5/6} + 1.71 \dfrac{k\rho^2}{L} - .024(\dfrac{k\rho^2}{L})^2 & , \quad \ell_0 << \rho << \sqrt{\lambda L} \\ - .0242(\dfrac{k\rho^2}{4L})^{-7/6} & , \quad \sqrt{\lambda L} << \rho \end{cases} \tag{3.9}$$

where ℓ_0 is the small scale of turbulence and is assumed to be 3mm in the Lowtran code, and σ_χ is the same as in Eq. (2.8). After substituting Eq. (3.8) (2.8) and (3.6) into (3.5), we can find the receiver aperture averaging effect for horizontal paths.

(ii) Slant path

Using Rytov Method, Kolmogorov spectrum and locally homogeneus medium, the correlation function of log-amplitude can be found from Ref. (2) under the condition $L\lambda >> \ell_0^2$:

$$B_\chi(L,\rho) = .033\, \pi^2(- \Gamma(- \frac{5}{6}))\, k^2 \cdot \int_0^L C_n^2\, (\eta)\, d\eta \cdot FG(\rho,\eta) \tag{3.10}$$

where

$$FG(\rho,\eta) = \Big[\mathrm{Re}\, (\frac{1}{\kappa_m^2} + \frac{i(L - \eta)}{k})^{5/6} {}_1F_1(- \frac{5}{6}, 1, - \frac{\rho^2}{4(\frac{1}{\kappa_m^2} + \frac{i(L - \eta)}{k})})$$

$$- \left(\frac{1}{\kappa_m^2}\right)^{5/6} {}_1F_1\left(-\frac{5}{6}, 1, -\frac{\kappa_m^2 \rho^2}{4}\right) \Bigg] \tag{3.11}$$

$$\kappa_m \equiv \frac{5.92}{\ell_0} \tag{3.12}$$

${}_1F_1(a,b,x)$ is the degenerate hypergeometric function#. For calculating ${}_1F_1$ on the computer, we approximate the function ${}_1F_1$ as

$${}_1F_1\left(-\frac{5}{6}, 1, X\right) = \begin{cases} 1 - 0.8333X - 0.0347X^2 - 0.0045X^3 & |X| < 6.5 \\ 1.0627(-X)^{5/6} & |X| \geq 6.5 \text{ and } (\mathrm{Re}\, X < 0) \end{cases} \tag{3.13}$$

This approximation has been checked and the total error is under 10%. Furthermore, we assume $\frac{L - \eta}{k} >> \frac{1}{\kappa_m^2}$, which means that we neglect very small parts of turbulence near the receiver. We then substitute Eq. (3.13) into (3.11), and get the different forms for the different conditions:

$$FG(\eta, \rho) = \begin{cases} 0 & \left(\frac{\rho^2}{4D} > 6.5,\ \frac{\rho^2}{4A} > 6.5\right) \\ D^{5/6}\left(.259 + .805 \frac{\rho^2}{4D} + .009\left(\frac{\rho^2}{4D}\right)^2 - .0043\left(\frac{\rho^2}{4D}\right)^3\right) & \\ \quad - 1.065(\rho^2/4)^{5/6} & \left(\frac{\rho^2}{4D} < 6.5,\ \frac{\rho^2}{4A} > 6.5\right) \\ D^{5/6}\left(.259 + .805 \frac{\rho^2}{4D} + .009\left(\frac{\rho^2}{4D}\right)^2 - .0043\left(\frac{\rho^2}{4D}\right)^3\right) & \\ \quad - (A)^{5/6}\left(1 + .8333 \frac{\rho^2}{4A} - .0347\left(\frac{\rho^2}{4A}\right)^2 + .0045\left(\frac{\rho^2}{4A}\right)^3\right) & \\ & \left(\frac{\rho^2}{4D} < 6.5,\ \frac{\rho^2}{4A} < 6.5\right) \end{cases} \tag{3.14}$$

#Note that an equation for a similar situation given by Ishimaru (A. Ishimaru, "Wave Propagation and Scattering in Random Media", Academic Press 1978, Vol. 2, Eq. 17-112) is in error.

where

$$D \equiv \frac{L - \eta}{k} \quad , \quad A \equiv \frac{1}{\kappa_m^2} \tag{3.15}$$

Putting Eq. (3.13) into (3.10) and changing the integration into summation we get

$$B_\chi(\rho) = 2.17\,k^2 \sum_i \sum_j C_n^2\,(h_{ij})\,FG(L_{ij})\,\frac{\Delta L_i}{h_i - h_{i-1}}\,\Delta h_{ij} \tag{3.16}$$

where k is the wavenumber, L is the path length, "i" is the layer index, "j" is the subindex in each layer, $C_n^2(h_{ij})$ is the structure constant at the height h_{ij}, h_{ij} is the altitude of the point calculated, and ΔL_i is the path length in each layer. Similarly, putting Eq. (2.10), (3.6), (3.16) into (3.5) and changing it into summation we get

$$G(R) = \frac{16}{\pi} \sum_{i=1}^{100} b_I(2Ry_i)\,[\cos^{-1}(y_i) - y_i\sqrt{1 - y_i^2}\,]\,y_i \cdot .01 \tag{3.17}$$

where "R" is the radius of the receiver aperture, i is the summation index, and $y_i = 0.01i$.

The intensity deviation $\sigma_p(R)$ for a finite aperture receiver can now be obtained by multiplying G(R) and σ_I (Eq. 2.5)

$$\sigma_p(R) = \sigma_I \cdot \sqrt{G(R)} \tag{3.18}$$

For a condition of moderate turbulence $C_n^2 = 2 \cdot 10^{-16}\ m^{-2/3}$ and horizontal propagation with path length, L = 5km, the aperture averaging coefficient G(R) is shown as solid line in Fig. (3.1). It is similar to the dashed line 2 in Fig. (3.1) predicted by Tatarskii[2]. The dashed line 1 in Fig. (3.1) shows the aperture averaging coefficient G(R) for downward path with altitude from 200m to 4km. Comparing horizontal and downward cases, we see that aperture averaging has more effect for the horizontal case. This is because the total turbulence in the case of horizontal path is stronger than the downward case and the coherence length of field of latter is longer than the former.

Figs. (3.2), (3.3) and (3.4) show the atmospheric transmittance predicted by the modified Lowtran V with diameter of the aperture being 30cm, for horizontal, downward and upward path, respectively.

IV. Subroutine of intensity deviation for Lowtran V

This subroutine is for the calculation of intensity deviation, due to turbulence, which can be used to define the upper bound and the lower bound of plane wave transmittance for the point receiver case and the finite aperture receiver case. The subroutine for each calculation of transmittance and for each frequency is called by subroutine TRANS, one of the subroutines of the main program. According to horizontal path, downward path, upward path, we divide the subroutine into three parts. The attached flow chart shows the main points of the subroutine (See Appendix A). We transfer the data of path altitudes H1 and H2, path length L, wavenumber k, the path length in each layer DS1 , DS2, the height in each layer XW1, XW2, and the diameter of the receiver# and other necessary data to the subroutine VRANI from the main program or from the subroutines of the main program. The symbols and definitions of variables used in the subroutine are listed in Appendix B. The program listing is in Appendix C.

V. Limitations and comments

The subroutine for intensity deviation is theoretically formulated by Rytov's Method. Even after our modification, Eq. (2.5) is only valid for weak and extremely strong turbulence. For moderate turbulence the theory under estimates the fluctuations of intensity as compared with experimental data. Second, in this program we only consider the plane wave case, hence, it will

#The diameter of the receiver must be read in from the sixth variable of the second control card and the format is F10.3 and in units of meters.

overestimate the fluctuation in weak turbulence for a real source such as a beam-wave or spherical wave.

For the turbulence itself, we use the model given in Ref. 5, which seems to be too simple to give satisfactory result. Hopefully, we can find a more proper form of turbulence profile in the future and update it in the code. In fact, turbulence in the atmosphere should be varying with temperature, wind speed and constituents of the atmosphere. It is suggested that the turbulence model, like the aerosol models or atmospheric models in Lowtran, should be constructed by different models based on different areas and seasons.

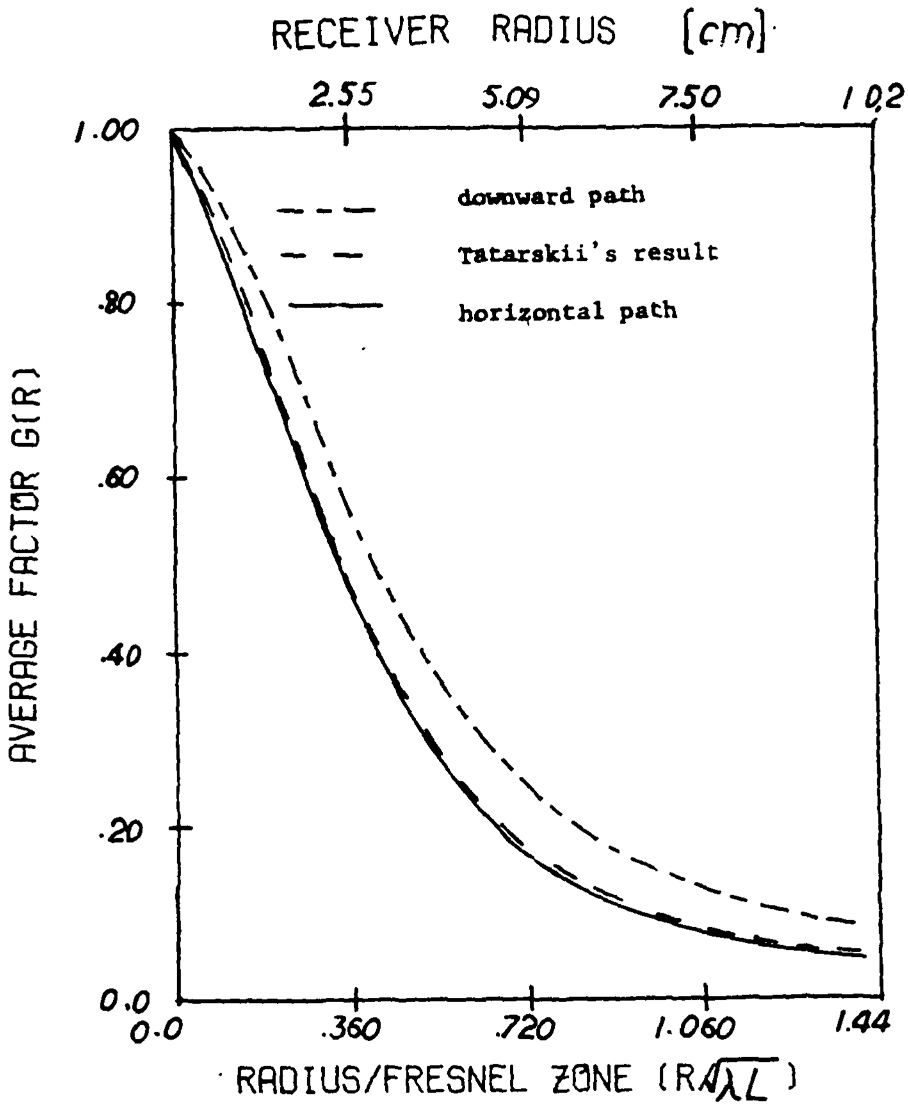


Fig. 3-1 Comparison of aperture averaging factors G(R) for different situations. Solid line is predicted by the new subroutine for a horizontal path at altitude h = 400m. Dashed line 1 (— - —) is predicted by the new subroutine for a downward path at altitude from 200m to 4km. Dashed line 2 (— —) is predicted by Tatarskii. The wavelength is $\lambda = 1 \mu m$ and path length is L = 5km.

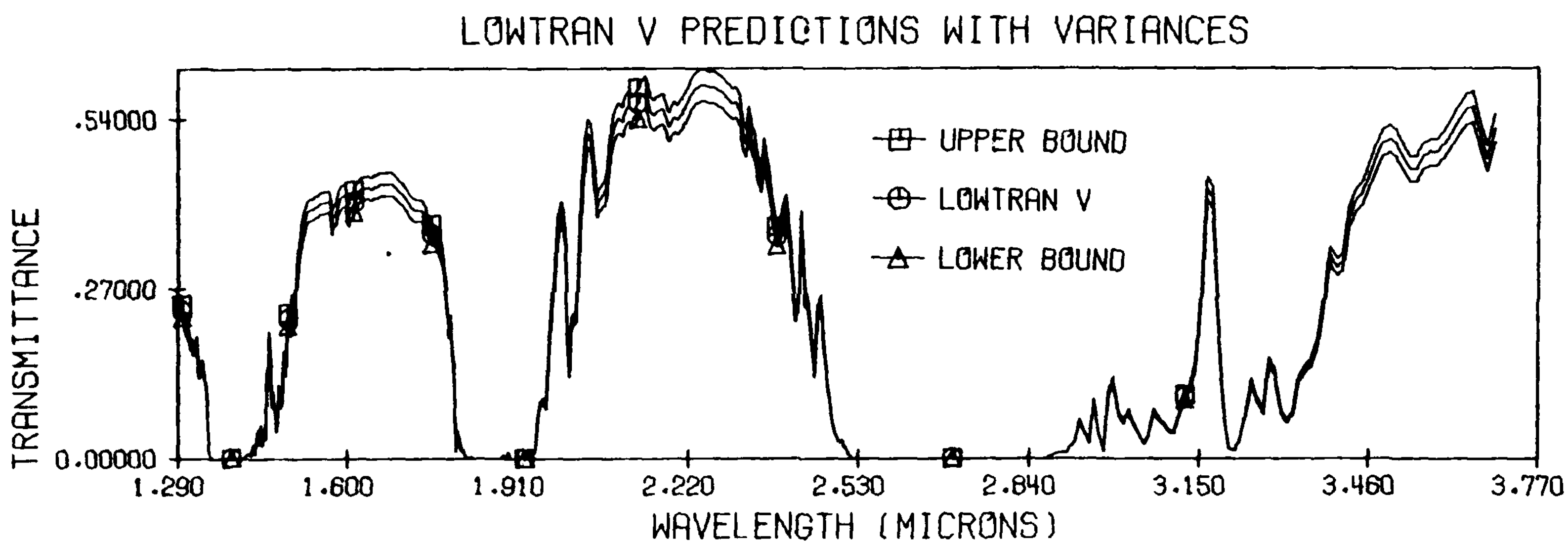


Fig. 3-2 Atmospheric transmittance predicted by the modified LOWTRAN V with upper bound and lower bound using 1962 U.S. standard atmospheric model and Rural aerosol model for a 5 km horizontal path at altitude 400 m, visual range 5 km and a finite receiver of diameter 30 cm.

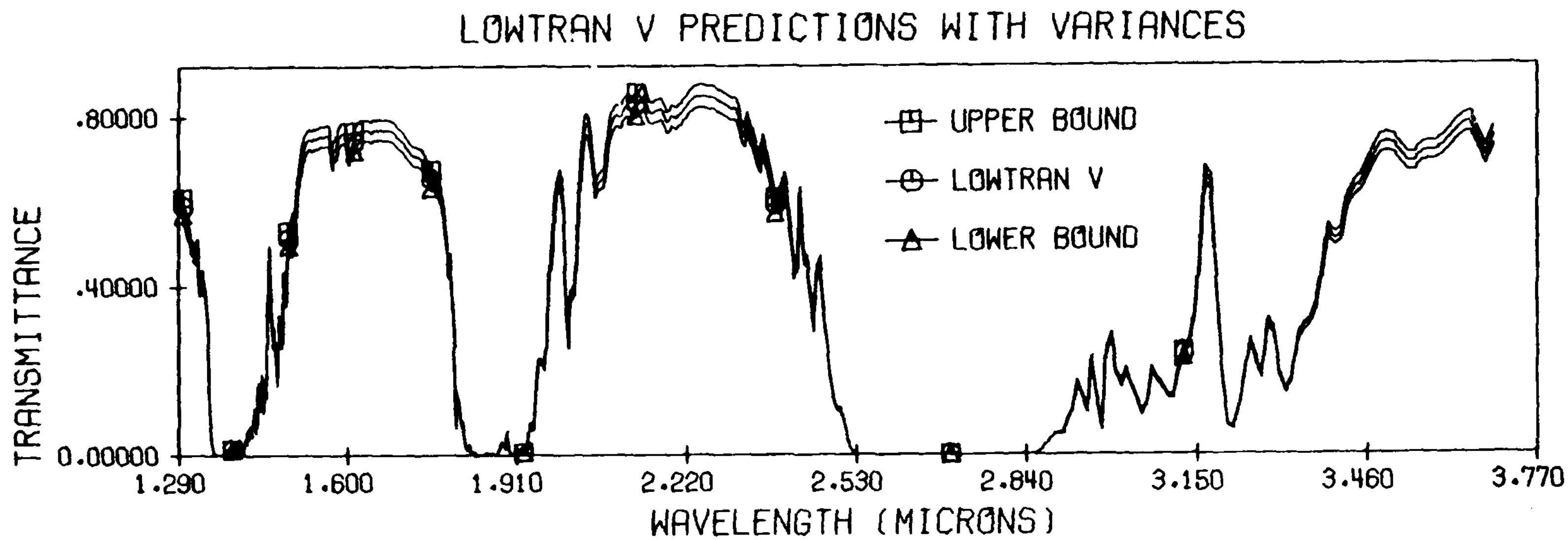


Fig. 3-3 Atmospheric transmittance predicted by the modified LOWTRAN V with upper bound and lower bound using 1962 U.S. standard atmospheric model and Rural aerosol model for a downward path at altitude from 200 m to 4 km with path of 5 km, visual range 5 km, and a finite aperture receiver of diameter 30 cm.

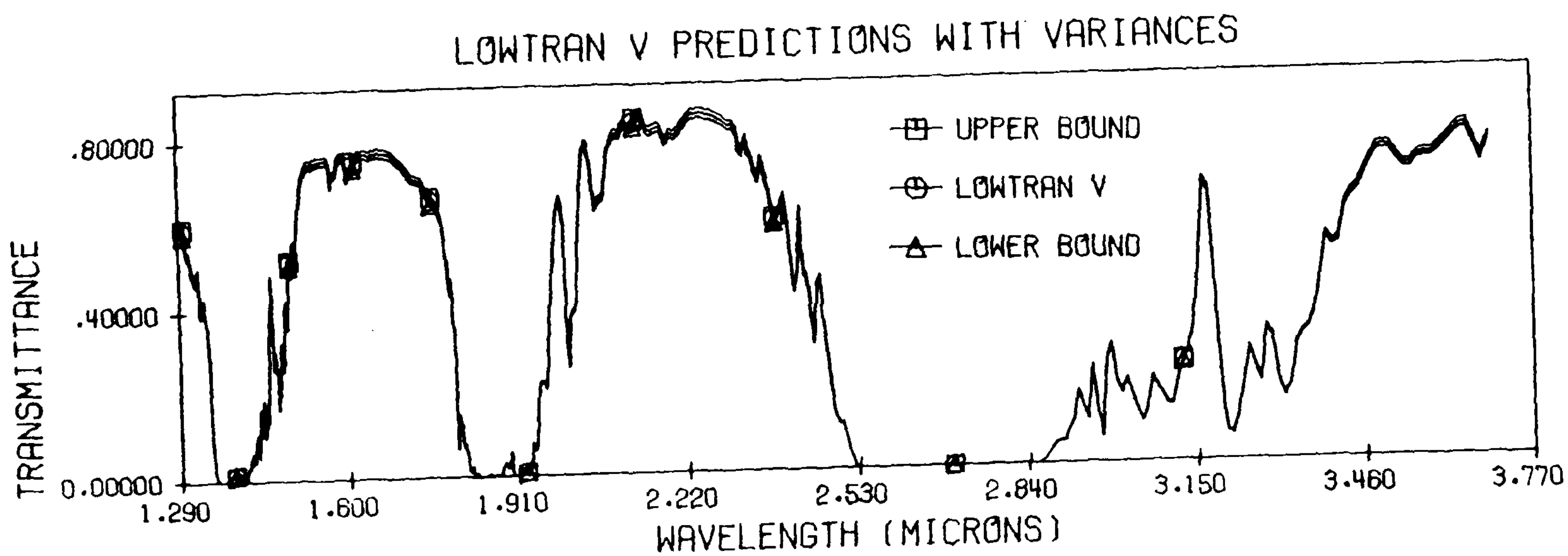
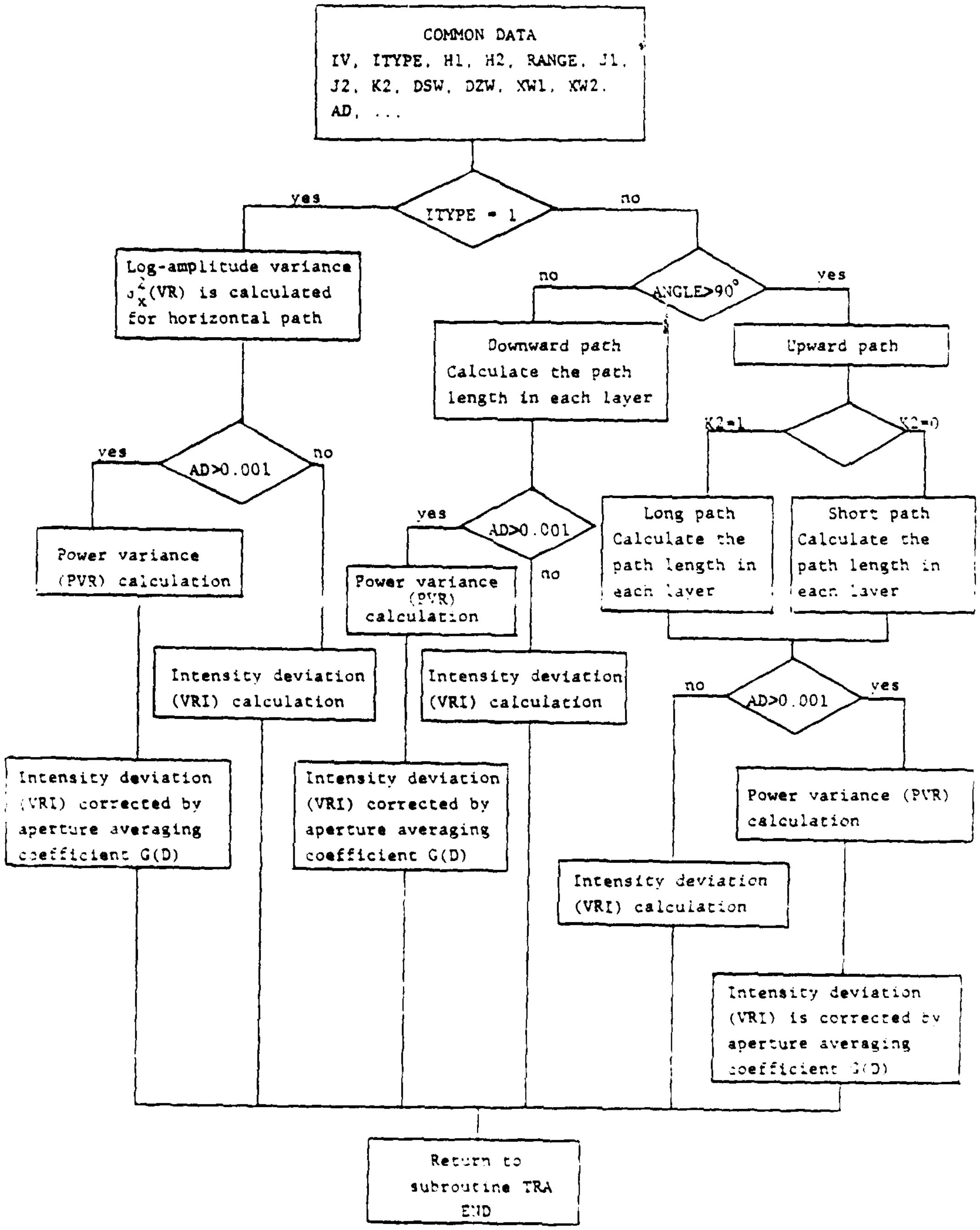


Fig. 3-4 Atmospheric transmittance predicted by the modified LOWTRAN V with upper bound and lower bound using 1962 U.S. standard model and Rural aerosol model for a 5 km upward path at altitude from 4 km to 200 m with visual range 5 km, and a 30 cm diameter aperture receiver.

APPENDIX A

Flow Chart of Subroutine VRANI



APPENDIX B

VRANI Symbols and Definitions

AD Diameter of receiver aperture in meter (m).

ANGLE Initial zenith angle in degree

BI Covariance of intensity

BL Normalized covariance of log-amplitude

BX Covariance of log-amplitude

CN2 C_n^2 - structure constant of turbulence

DD the ratio of the distance from point calculated to receiver over total path length.

DH Height interval of slant path integration

DS Distance from point calculated to receiver

DT Same as DS, especially used in the downward long path calculation

DZW Difference of height between two near layers

FR Fresnel zone in meter (m)

GD Aperture averaging coefficient

HMIN The minimum height of a downward path

HW Height corresponding to the point calculated

H1 Height of transmitter (and receiver for horizontal path)

H2 Height of receiver

IV wavenumber in cm^{-1}

JMIN the layer index of the minimum height for a downward path

RANGE	Path length in kilometer (km)
VR	Variance of log-amplitude
VRI	Intensity deviation
PVR	Power variance
DSW	Path length in a layer
WH2	Height of receiver in meter (m)
WL	Wavelength in meter (m)
WK	$2\pi/\lambda$, wavenumber in m^{-1}
WRANGE	Path length in meter (m)
WV	Intensity variance without approximation
XW1	The lowest height of a given path in a given layer
XW2	The highest height of a given path in a given layer

APPENDIX C

Listing of Subroutine VRANI Program

```
      SUBROUTINE VRANI(IV)
C
C     THIS SUBROUTINE IS TO CALCULATE THE VARIANCE OF INTENSITY
C     DUE TO TURBULENCE  AND THE CALCULATED STANDARD DEVIATION CAN BE
C     USED TO DEFINE HIGH BOUND AND LOW BOUND OF TRANSMITTANCE
C
      COMMON /CARD1/ MODEL,IHAZE,ITYPE,LEN,JP,IM,M1,M2,M3,ML,IEMISS,RO
     1 ,TBOUND,ISEASN,IVULCN,VIS
      COMMON /CARD2/ H1,H2,ANGLE,RANGE,BETA,HMIN,RE,AD
      COMMON /CARD3/ V1,V2,DV,AVW,CO,CW,W(15),E(15),CA,PI
      COMMON /CNTRL/ LENST,KMAX,M,IJ,J1,J2,JMIN,JEXTRA,IL,IKMAX,NLL,NPI
     1,IFIND,NL,IKLO
      COMMON /WANG/ K2,USW(34),UZW(34),XW1(34),XW2(34)
      COMMON /VRAN/ VRI
      DIMENSION WS(34)
      HW=H1*1000.0
      WRANGE=RANGE*1000.0
      WH2=H2*1000.0
      VR=0.0
      CN2=0.0
      PVR=0.0
      WL=0.01/IV
      FR=(WL*WRANGE)**0.5
      WK=IV*100.*2.*PI
      VK=WK**(7./6.)
      WO=9.E-6/5.910**2.
      IF(ITYPE.NE.1) GO TO 20
C
C      VARIANCE CALCULATION FOR HORIZONTAL PATH
C
      CN2=4.2E-14*HW**(-2./3.)*EXP(-HW/320.0)
      IF(H1.GT.100.0) CN2=0.0
      IF(HW.LE.10.0) CN2=8.77E-15
      VR=0.31*CN2*WRANGE**(11./6.)
      VR=VR*VK
      VRI=1.-EXP(-2.*VR**0.5)
      IF(AD.LT.0.001) GO TO 91
      DO 18 I=1,100
      Y=0.01*I
      DY=AD*Y
      IF(DY.GE.0.003) GO TO 11
      BL=1.-12.3*DY**2.0/(FR**(5./3.)*0.003**(1./3.))
      GO TO 17
   11 XI=WK*DY**2.0/WRANGE
      IF(DY.GE.FR) GO TO 12
      BL=1.-2.36*XI**(5./6.)+1.71*XI-0.024*XI**2.0
      GO TO 17
   12 BL=-0.0242*(XI/4.)**(-7./6.)
   17 CONTINUE
      BX=BL*VR
      BI=EXP(4.0*BX)-1.
      PVR=PVR+BI*(ACOS(Y)-Y*(1.-Y**2.)**0.5)*Y*0.01
   18 CONTINUE
      PVR=PVR*16./PI
      WV=EXP(4.0*VR)-1.
      GO=PVR/WV
      VRI=VRI*GO**0.5
      GO TO 91
   20 IF(ANGLE.GT.90.0) GO TO 37
C
C      VARIANCE CALCULATION FOR DOWNWARD PATH
C
```

```
      DO 35 K=1,100
      DS=0.0
      BX=0.0
      Y=0.01*K
      DY=AD*Y
      RF=DY**2./4.
      VR=0.0
      Q=RF/W0
      DO 34 I=J1,J2
      WS(I)=DSW(I)/DZW(I)
      IF(XW1(I).LE.25.0) GO TO 21
      IF(XW1(I).LE.50.0) GO TO 22
      DH=400.0
      GO TO 23
   21 DH=20.0
      GO TO 23
   22 DH=100.0
   23 WIK=(XW2(I)-XW1(I))*1000.0/DH
      IK=WIK
      HW=XW1(I)*1000.0
      DO 33 J=1,IK
      HW=HW+DH
      IF(HW.GE.99600.0.AND.ITYPE.EQ.3) XW2(I)=100000.0
      IF(HW.GE.99600.0) GO TO 34
      CN2=4.2E-14*HW**(-2./3.)*EXP(-HW/320.0)
      VR=VR+0.56*CN2*(WRANGE-DS)**(5./6.)*DH*WS(I)
      DD=(WRANGE-DS)/WK
      R=RF/DD
      IF(DD.LT.W0) GO TO 27
      IF(R.GE.6.5.AND.Q.GE.6.5) GO TO 27
      IF(R.LT.6.5.AND.Q.LT.6.5) GO TO 28
      G=DD**(5./6.)*(0.259+0.805*R+0.009*R**2.-0.0043*R**3.)-1.063*RF**(
     *5./6.)
      IF(G.LE.0.0) G=0.
      GO TO 31
   27 G=0.0
      GO TO 31
   28 G=DD**(5./6.)*(0.259+0.305*R+0.009*R**2.-0.0013*R**3.)-W0**(5./6.)
     **(1.+0.0333*Q-0.2347*Q**2.+0.0045*Q**3.)
      IF(G.LE.0.0) G=0.0
   31 BX=BX+G*CN2*DH*WS(I)
      DS=DS+DH*WS(I)
   33 CONTINUE
      DG=WRANGE-DS
      IF(DG.LE.0.) DS=DS-DH*WS(I)
      VR=VR+0.56*CN2*(WRANGE-DS)**(5./6.)*(XW2(I)*1000.-HW)*WS(I)
      BX=BX+CN2*G*(XW2(I)*1000.-HW)*WS(I)
      DS=DS+(XW2(I)*1000.0-HW)*WS(I)
   34 CONTINUE
      IF(AD.LT.0.001) GO TO 36
      BX=BX*2.117*WK**2.
      BI=EXP(4.*BX)-1.
      PVR=PVR+BI*(ACOS(Y)-Y*(1.-Y**2.)**0.5)*Y*0.01
   35 CONTINUE
      PVR=PVR*16./PI
   36 VR=VR*VK
      VRI=1.-EXP(-2.*VR**0.5)
      IF(AD.LT.0.001) GO TO 91
      AV=EXP(4.*VR)-1.
      GU=PVR/AV
      VRI=VRI*GU**0.5
      GO TO 91
```

```
   37 CONTINUE
C
C      VARIANCE CALCULATION FOR UPWARD PATH
C
      DO 62 MW=1,100
      DS=0.0
      DT=0.0
      DX=0.0
      Y=0.01*MW
      DY=AU*Y
      RF=DY**2./4.
      VR=0.0
      Q=RF/WO
      L1=J1
      DO 60 L=1,NL
      L1=L1-1
      WS(L1)=DSW(L1)/DZW(L1)
      IF(XW1(L1).LE.25.0) GO TO 38
      IF(XW1(L1).LE.50.0) GO TO 39
      DH=400.0
      GO TO 40
   38 DH=20.00
      GO TO 40
   39 DH=100.00
   40 WIK=(XW1(L1)-XW2(L1))*1000.0/DH
      IK=WIK
      HW=XW1(L1)*1000.0
      DO 57 J=1,IK
      HW=HW-DH
      CN2=4.2E-14*HW**(-2./3.)*EXP(-HW/320.0)
      VR=VR+0.56*CN2*(WRANGE-DS)**(5./6.)*DH*WS(L1)
      DU=(WRANGE-DS)/WK
      R=RF/DU
      IF(DU.LT.WO) GO TO 51
      IF(R.GE.6.5.AND.Q.GE.6.5) GO TO 51
      IF(R.LT.6.5.AND.Q.LT.6.5) GO TO 52
      G1=DU**(5./6.)*(0.259+0.805*R+0.209*R**2.-0.0043*R**3.)-1.063*RF**
     *(5./6.)
      IF(G1.LE.0.) G1=0.
      GO TO 53
   51 G1=0.0
      GO TO 53
   52 G1=DU**(5./6.)*(0.259+0.805*R+0.009*R**2.-0.0043*R**3.)-WO**(5./6.
     *)*(1.+0.0333*Q-0.0347*Q**2.+0.0045*Q**3.)
      IF(G1.LE.0.0) G1=0.0
   53 DX=DX+G1*CN2*DH*WS(L1)
      DS=DS+DH*WS(L1)
      IF(K2.EQ.0) GO TO 57
      IF(K2.EQ.1.AND.HH2.LE.HW) GO TO 57
      VR=VR+0.56*CN2*DT**(5./6.)*DH*WS(L1)
      DU=DT/WRANGE
      R=RF/DU
      IF(DU.LT.WO) GO TO 54
      IF(R.GE.6.5.AND.Q.GE.6.5) GO TO 54
      IF(R.LT.6.5.AND.Q.LT.6.5) GO TO 55
      G2=DU**(5./6.)*(0.259+0.805*R+0.009*R**2.-0.0043*R**3.)-1.063*RF**
     *(5./6.)
      IF(G2.LE.0.) G2=0.
      GO TO 56
   54 G2=0.0
      GO TO 56
   55 G2=DU**(5./6.)*(0.259+0.805*R+0.009*R**2.-0.0043*R**3.)-WO**(5./6.
```

```
     *)*(1.+0.0333*Q-0.0347*Q**2.+0.0045*Q**3.)                          AVR 0187
      IF(G2.LE.0.0) G2=0.0                                              AVR 0188
   56 BX=BX+G2*CN2*DH*WS(L1)                                            AVR 0189
      DT=DT+DH*WS(L1)                                                   AVR 0190
   57 CONTINUE                                                          AVR 0191
      DQ=WRANGE-DS                                                      AVR 0192
      IF(DQ.LE.0.) DS=DS-DH*WS(L1)                                      AVR 0193
      VR=VR+0.56*CN2*(WRANGE-DS)**(5./6.)*(HW-XW2(L1)*1000.)*WS(L1)     AVR 0194
      BX=BX+G1*CN2*(HW-XW2(L1)*1000.)*WS(L1)                            AVR 0195
      DS=DS+(HW-XW2(L1)*1000.0)                                         AVR 0196
      IF(K2.EQ.0) GO TO 58                                              AVR 0197
      IF(K2.EQ.1.AND.HH2.LE.HW) GO TO 58                                AVR 0198
      VR=VR+0.56*CN2*DT**(5./6.)*(HW-XW2(L1)*1000.)*WS(L1)              AVR 0199
      BX=BX+G2*CN2*(HW-XW2(L1)*1000.)*WS(L1)                            AVR 0200
      DT=DT+(HW-XW2(L1)*1000.0)*WS(L1)                                  AVR 0201
   58 CONTINUE                                                          AVR 0202
      IF(K2.EQ.0.AND.L1.LE.J2) GO TO 61                                 AVR 0203
      IF(L1.LE.JMIN.AND.K2.EQ.1) GO TO 61                               AVR 0204
   60 CONTINUE                                                          AVR 0205
   61 CONTINUE                                                          AVR 0206
      IF(AO.LT.0.001) GO TO 90                                          AVR 0207
      BX=BX*2.117*WK**2.                                                AVR 0208
      BI=EXP(4.*BX)-1.                                                  AVR 0209
      PVR=PVR+BI*(ACOS(Y)-Y*(1.-Y**2.)**0.5)*Y*0.01                     AVR 0210
   62 CONTINUE                                                          AVR 0211
      PVR=PVR*16./PI                                                    AVR 0212
   90 VR=VR*VK                                                          AVR 0213
      VRI=1.-EXP(-2.*VR**0.5)                                           AVR 0214
      IF(AO.LT.0.001) GO TO 91                                          AVR 0215
      WV=EXP(4.*VR)-1.                                                  AVR 0216
      GD=PVR/WV                                                         AVR 0217
      VRI=VRI*GD**0.5                                                   AVR 0218
   91 CONTINUE                                                          AVR 0219
      RETURN                                                            AVR 0220
      END                                                               AVR 0221
```

References

1. F. X. Kneizys et. al., Atmospheric Transmittance/Radiance: Computer Code Lowtran 5, AFGL-TR-80-0067, Environmental Research Papers, No. 697.

2. V. I. Tatarskii, "The Effects of the Turbulent Atomosphere on Wave Propagation, NTIS, Springfield, 1971.

3. S. C. H. Wang, M. A. Plonus and C. F. Ouyang, "Irradiance scintillations of a partially coherent source in extremely strong turbulence", Applied Optics, Vol. 18, p. 113-1135, 1979.

4. M. A. Plonus, Proposal for Air Force Contract F19628-79-(-0068).

5. R. E. Hufnagel and N. R. Stanley, "Modulation transfer function associated with image transmission through turbulent Media", J. Opt. Soc. Am., Vol. 54, p. 52-61, 1964.

6. R. S. Lawrence and J. W. Strohbehn, "A survey of clear-air propagation effects relavant to optical communications", Proc. IEEE, Vol. 58, p. 1523-1545, 1970.

7. M. E. Gracheva, A. S. Gurvich, S. S. Kashkarov and V. V. Pokasov, "Similarity relations and their experimental verification for strong intensity fluctuations of laser radiation", in chap. 4 of Topics in Applied Physics Vol. 25, Editor by J. W. Strohbehn, Springer-Verlag, New York, 1978

8. J. R. Kerr, "Experiments on turbulence characteristics and multiwave-length scintillation phenomena", J. Opt. Soc. Am., Vol. 62, p. 1040-1049, 1972.